Energy Policy 123 (2018) 184–197

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Carbon emissions reductions oriented dynamic equilibrium strategy using biomass-coal co-firing

Jiuping Xu[a,b,*], Qian Huang[a], Chengwei Lv[b], Qing Feng[b], Fengjuan Wang[b]

[a] Business School, Sichuan University, Chengdu 610064, PR China
[b] Institute of New Energy and Low-Carbon Technology, Sichuan University, Chengdu 610064, PR China

ARTICLE INFO

Keywords:
Carbon emissions reduction
Biomass-coal co-firing method
Dynamic equilibrium strategy

ABSTRACT

Carbon emissions are posing continuing threats to climate change and becoming the important evaluation indicator for sustainable development. The amount of global carbon emission is increasing largely, with coal-fired power plants (CPP) being the major contributor. This study proposes dynamic equilibrium strategy based on biomass-coal co-firing method to reduce carbon emissions, in which bi-level programming method is employed to build a cooperative relationship between the authority and CPPs, dynamic programming method is used to handle biomass availability time conflict, multi-objective programming method is applied to seek the trade-off between economic development and environmental protection, and furthermore uncertainty theory is introduced to address imprecise uncertain parameters. The proposed model is then applied to a case in Jiangsu, China, to demonstrate its efficiency and practicality, and an interactive algorithm is developed as the solution approach to represent the objectives and limitations between several stakeholders. Based on analyses and discussions under different scenarios, the proposed method can achieve economic-environmental coordination and realize sustainable development, and moreover a carbon emissions allocation competition mechanism is recommended. This methodology could be used in various countries and industries with only slight adjustments needed to some parameters.

1. Introduction

Global energy consumption has significantly increased in recent decades due to rapid urbanization, industrial development, world economic growth and rising populations (Mallick et al., 2017). The BP statistical review of world energy stated that in 2017, coal still accounted for 28.1% of global primary energy consumption and was ranked second after oil as an energy source. However, reliance on coal has resulted in excessive greenhouse gas emissions such as carbon emissions that have significantly contributed to global climate change (Pain, 2017; Basu, 1999; Li et al., 2009). According to BP Energy Outlook 2018, global carbon emissions have been growing relentlessly for nearly 50 years, although the growth has gradually slowed in recent year (Global, 2018). Global carbon emissions have risen from 16 Gt in 1970 to 36 Gt in 2015, an increase of 125% (Olivier et al., 2015). The concentration of carbon emissions in the atmosphere is the largest global environmental risk (Programme, 2017). Two thirds of the world's electricity is generated by fossil fuel power plants, of which coal-fired power plant (CPP) is one of largest sources of carbon emissions (Global, 2015; Service, 2017). Under these circumstances, carbon emissions from CPPs need to be urgently reduced.

Relevant studies on reducing carbon emissions from CPPs have focused on either hard-technology or soft-technology (Lv et al., 2016). Hard-technology, which concentrates on technological innovation or investment to reduce carbon emissions, is regarded as the most effective solution. Mao et al. (2014) claimed that coal washing, retrofitting the stream turbine flow passage, and carbon capture and storage/sequestration were all viable technical reduction measures, and Low et al. (2017) suggested utilizing TiO_2 to increase carbon dioxide adsorption. Although hard-technology has had a significant positive effect on carbon emissions reductions, it is generally expensive and beyond the ability of most developing countries (Xu et al., 2017). Therefore, soft-technology has been the more favored option (Goto et al., 2013; Xu et al., 2015; Li, 2012). Soft-technology seeks to modify the production operations or management methods without technological change and generally involves optimization methods or policy developments such

* Corresponding author at: Business School, Sichuan University, Chengdu 610064, PR China.
E-mail address: xujiuping@scu.edu.cn (J. Xu).

https://doi.org/10.1016/j.enpol.2018.08.043
Received 10 February 2018; Received in revised form 21 July 2018; Accepted 19 August 2018
Available online 01 September 2018

as co-firing, carbon tax, and Cap-and-Trade (C&T) (Chen et al., 2015; Dai et al., 2014; Yearwood-Lee, 2015; Broek et al., 1996). Lin and Li (2011) claimed that although carbon tax was an immediate carbon price signal, it also had some disadvantages as the mitigation impacts were uncertain and rational carbon tax rates were hard to determine. Keohane (2009) and Grubb (2012) believed that C&T had some advantages over carbon tax as it was political feasibility, cost effectiveness and was able to control the cumulative quantity of carbon emissions; however, its procedures are complex and cost is relatively high. In this situation, biomass-coal co-firing method provides the simplest, most practicable and most cost-effective method for carbon emissions reductions (Baxter, 2005; Li et al., 2012; Liu et al., 2016; Tilman et al., 2009).

Biomass-coal co-firing has been extensively researched. This method has been proved to be a reasonable option for power generation and has been found to significantly reduce the environmental footprint of CPPs as it reduces not only net greenhouse gases but also SO_2 and NO_x emissions because of biomass' lower carbon, sulfur, and fuel-bound nitrogen (Agbor et al., 2014; Hubweber et al., 2001; Weldu, 2017; Narayanan and Natarajan, 2007; Beagle and Belmont, 2016). Eksioglu and Karimi (2014) developed a non-linear optimization model from the perspective of CPPs that considered the additional costs and savings, loss of process efficiencies. And Yilmaz and Selim (2015) developed a fuzzy multi-objective strategy based decision making model to design the most profitable biomass supply chain. Several co-firing technologies have reached maturity; for example, Al-Mansour and Zuwala (2010) outlined three mature technological approaches: direct co-firing, in which biomass and coal were burned in the same or separate mills and burners; indirect co-firing, in which biomass a gasifier was installed to convert biomass into the coal furnace; parallel co-firing, in which separate biomass boiler and coal boiler were utilized. Basu et al. (2011) compared capital and operating costs of co-firing technologies in five CPPs, and concluded that direct co-firing method at lower ratios was the simplest and the lowest cost option. However, the greatest challenges associated with biomass-coal direct co-firing were co-firing ratio and biomass storage (Agbor et al., 2014; Rentizelas et al., 2009; Allen et al., 1998). Sahu et al. (2014) and Moon et al. (2013) found that a 10% biomass co-firing ratio was the peak acceptable mixing ratio for direct co-firing that had no irresolvable issues. To deal with biomass storage seasonal availability, Rentizelas et al. (2009) proposed combining multiple biomass supply chains to achieve the lowest cost storage. Although these studies have made some progress in addressing carbon emissions, they have tended to focus only on a single decision maker, only on economic development or only on biomass storage from a short-term perspective. The realistic situation is more complicated and further improvements are still necessary.

In this paper, a dynamic equilibrium strategy based bi-level multi-objective multistage biomass-coal co-firing method is proposed to reduce carbon emissions. In reality, there are several decision makers involved in carbon emissions reductions: the authority and the CPPs. The authority first makes an initial decision based on optimizing itself and predicting CPPs' decisions, after which the CPPs make decisions to satisfy the authority's decisions and profits maximization objective. As the CPPs' decisions could influence the authority's objectives, these are fed back to the authority. Then the authority adjusts its initial decision, following which the CPPs again make decisions and provide feedback. This process is repeated until a final scheme acceptable to the authority and all the CPPs is determined (Lv et al., 2016; Zhang et al., 2015). In the process, as the authority is the leader and CPPs are the followers, the relationship is similar to Stackelberg game. Therefore, bi-level programming method is adopted to seek a Stackelberg-Nash equilibrium (Colson et al., 2007; Sinha et al., 2014). As for the authority, it attaches great importance to both economic development and environmental protection, and has an overall sustainable development objective. Therefore, multi-objective programming method is used to seek the trade-off between the economy and the environment. In this paper, carbon emissions minimization represents environmental protection objective due to their important role in global climate change, and revenue maximization represents economic development objective as it can guarantee economic and society stability and development. In regard to CPPs, secure and long-term biomass storage is critical. As seasonal availability occurs to biomass storage, dynamic programming method is applied to determine the optimal decisions in each stage to ensure that CPPs are able to maximize profits over a long-term perspective. Uncertainty theory is also adopted to estimate the exact value of the uncertain parameters such as emissions factors, which are uncertain because of the unstable combustion process (Xu and Zhou, 2011; Liu et al., 2015).

Based on the above discussion, to reduce carbon emissions, this paper proposes a comprehensive methodology that integrates bi-level programming method, multi-objective programming method and dynamic programming method to achieve a cooperative relationship between the authority and the CPPs, balance the trade-off between environmental protection and economic development, and settle biomass storage time conflicts under an uncertain environment. Mathematical modeling method is employed to express this dynamic equilibrium strategy based bi-level multi-objective multistage biomass-coal co-firing method in the following section.

2. Modeling

2.1. Assumptions

(1) Co-firing at low ratios does not pose any threat or major problems to the boiler operations (Basu et al., 2011).
(2) Volatile matter of fuels can be completely burnt in the burners (Sami et al., 2001).
(3) Value-added tax rate the CPPs pay is fixed.
(4) This method is a single production period, with the production period divided into 12 months; at the beginning of the each production period, the fuel storage is reset.

2.2. Model for the local authority

2.2.1. Objective 1: maximizing revenue

As it is difficult to deal with realistic uncertain decision making problems, uncertainty theory is used to assess the uncertain parameters. Uncertain parameters can be estimated to be within a certain range, in which the values of parameters are more likely to be. For instance, $\tilde{C}_{ji}$ is a trapezoidal fuzzy number, the certain range of which is from the minimum value r_{11} to the maximum value r_{14}, and the most likely value of which is between r_{12} and r_{13}. This trapezoidal fuzzy number can be written as $\tilde{C}_{ji} = (r_{11}, r_{12}, r_{13}, r_{14})$, where $r_{11} \le r_{12} \le r_{13} \le r_{14}$. To value the exact value of trapezoidal fuzzy numbers, the expected value operator method proposed by Xu and Zhou (2011) is adopted as Fig. 1.

$$\tilde{C}_{ji} \rightarrow E\left[\tilde{C}_{ji}\right] = \frac{1-\theta}{2}\left(r_{11} + r_{12}\right) + \frac{\theta}{2}\left(r_{13} + r_{14}\right) \tag{1}$$

To guarantee the stability and development of the economy and the society, the authority imposes value-added tax and fees on the carbon emissions quotas. Let M be value-added tax rate, and $\sum_{s=1}^{S}\sum_{i=1}^{I} QE[\tilde{C}_{ji}]x_{jis}$ represents the annual profits of CPP j; therefore,

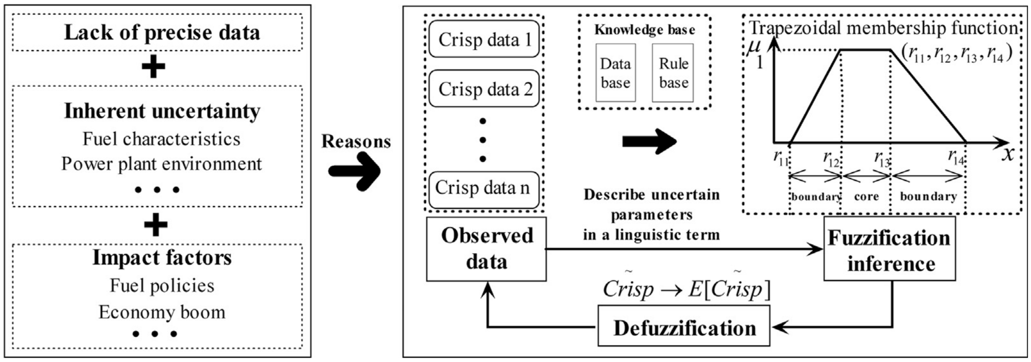


Fig. 1. Flowchart of fuzzy membership function.

the total value-added tax received from the various CPPs is $\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{i=1}^{I}MQE[\tilde{C}_{ji}]x_{jis}$. Let u be the price of per unit carbon emissions allocation quota and $\sum_{j=1}^{J}y_j$ be the total amount of carbon emissions allowances allocated by the authority; therefore, $u\sum_{j=1}^{J}y_j$ is derived. The total revenue is formulated as:

$$\max F_1 = \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{i=1}^{I}MQE\left[\tilde{C}_{ji}\right]x_{jis} + u\sum_{j=1}^{J}y_j \tag{2}$$

2.2.2. Objective 2: minimizing carbon emissions

Unlike other organizations, the authority is responsible to the public for environmental protection. Let y_j be carbon emissions quota allocated by the authority to CPP j. Combining all the CPPs in the region, $\sum_{j=1}^{J}y_j$ is obtained; therefore, the mathematical form is:

$$\min F_2 = \sum_{j=1}^{J}y_j \tag{3}$$

2.2.3. Limitations on the CPPs operations

As each CPP has the obligation to pay tax, its basic rights such as maintaining basic operation must also be assured by the authority. Q_j^L is the quantity of carbon emissions produced by CPP j when expenses balance receipts. y_j is carbon emissions allocation quota for CPP j; therefore, $Q_j^L \le y_j$. As the authority levies fees on carbon emissions quotas, it must allocate carbon emissions quotas that every CPP can carry. Q_j^U represents carbon emissions under full-load production in CPP j. Therefore, $y_j \le Q_j^U$. These constraints can be written as:

$$Q_j^L \le y_j \le Q_j^U \tag{4}$$

2.2.4. Power supply demand limitation

The authority has to ensure that the power supply is able to meet the region's requirements. Let $\tilde{H}_j$ be conversion parameters for a unit of carbon emissions to power for CPP j, and $E[\tilde{H}_j]y_j$ denotes electric power supplied by CPP j. The sum of all the CPPs is $\sum_{j=1}^{J}E[\tilde{H}_j]y_j$ and should exceed the amount of power needed in a region $\sum_{j=1}^{J}\sum_{s=1}^{S}U_{js}$. The mathematical constraint is formed as:

$$\sum_{j=1}^{J}E\left[\tilde{H}_j\right]y_j \ge \sum_{j=1}^{J}\sum_{s=1}^{S}U_{js} \tag{5}$$

2.2.5. Limitation on the gap between the quota and the actual value

Sometimes carbon emissions quota is far from the actual situation, which means that the CPPs need to pay for unused allocations. To rationally allocate carbon emissions quotas, the authority needs to take every CPPs' conditions into account when making decisions. Let $y_j - \sum_{s=1}^{S}\sum_{i=1}^{I}E[\tilde{CE}_{ji}]x_{jis}$ represent the difference between the quota and the actual value, therefore this constraint can be written as follows:

$$\frac{y_j - \sum_{s=1}^{S}\sum_{i=1}^{I}E\left[\tilde{CE}_{ji}\right]x_{jis}}{y_j} \le \lambda \tag{6}$$

2.3. Model for CPPs

2.3.1. Objective: maximizing profits

The CPPs are allocated a certain carbon emissions quota by the regional authority. Under this limited carbon emissions quota, the CPPs develop better 12 month production plans to obtain larger profits. In this paper, for CPP j, let Q be the unit price of electric power and $\sum_{s=1}^{S}\sum_{i=1}^{I}E[\tilde{C}_{ji}]x_{jis}$ denotes the electric power generated by CPP j; therefore, the annual value-added tax from the electric power sales is $Q\sum_{s=1}^{S}\sum_{i=1}^{I}E[\tilde{C}_{ji}]x_{jis}$. The cost can be divided into fuel purchase costs, fuel storage costs, pollutants treatment costs, taxes and fees on carbon emissions allowances. As biomass prices change from month to month, CPP j decides on the quantity z_{jis} to buy depending on the month, and $\tilde{P}_{jis}$ denotes the unit purchase price for fuel i in s month, which means that the annual fuel purchase costs are $\sum_{s=1}^{S}\sum_{i=1}^{I}E[\tilde{P}_{jis}]z_{jis}$. Storage is also necessary after purchases, and closing stock of the previous month plus the present month's purchase I_{jis} needs warehousing. Let Z be the per unit monthly storage price, therefore the fuel storage costs are $Z\sum_{s=1}^{S}\sum_{i=1}^{I}I_{jis}$. Let $\tilde{N}_{ik}$ be the pollutant emissions k resulting from burning a unit of fuel i and V_{jk} be the unit operating costs at CPP j for treating pollutant k; then, the total annual costs for pollutants treatment can be described as: $\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{k=1}^{K}E[\tilde{N}_{ik}]V_{jk}x_{jis}$. Let M be value-added tax, then tax cost could be $MQ\sum_{s=1}^{S}\sum_{i=1}^{I}E[\tilde{C}_{ji}]x_{jis}$. The cost of purchasing the carbon emissions quota is uy_j. Therefore, the profits at CPP j can be written as:

$$\begin{aligned}\max f = {} & Q\sum_{s=1}^{S}\sum_{i=1}^{I}E\left[\tilde{C}_{ji}\right]x_{jis} - \sum_{s=1}^{S}\sum_{i=1}^{I}E\left[\tilde{P}_{jis}\right]z_{jis} - Z\sum_{s=1}^{S}\sum_{i=1}^{I}I_{jis} \\ & - \sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{k=1}^{K}E\left[\tilde{N}_{ik}\right]V_{jk}x_{jis} - MQ\sum_{s=1}^{S}\sum_{i=1}^{I}E\left[\tilde{C}_{ji}\right]x_{jis} - uy_j\end{aligned} \tag{7}$$

2.3.2. Combustion efficiency constraint

The best combustion efficiency extracts energy from the fuels with the least amount of loss. Due to the relatively low calorific values and moisture content in fuel blends, biomass-coal possibly decreases overall efficiency (Dumortier, 2013). Let $\tilde{B}_{it}(t=1)$ be the volatile matter content and $\tilde{\eta}_i$ be the burn-out fraction of fuel i char; therefore $\sum_{i=1}^{I} E[\tilde{B}_{it}]x_{jis} + \sum_{i=1}^{I} E[\tilde{\eta}_i](1-E[\tilde{B}_{it}])x_{jis}$ is what can be burnt in the fuel blends (Sami et al., 2001). α is combustion efficiency. Therefore co-combustion efficiency of the fuel blends is:

$$\frac{\sum_{i=1}^{I} E\left[\tilde{B}_{it}\right]x_{jis} + \sum_{i=1}^{I} E[\tilde{\eta}_i]\left(1-E\left[\tilde{B}_{it}\right]\right)x_{jis}}{\sum_{i=1}^{I} x_{jis}} \geq \alpha \tag{8}$$

2.3.3. Fuel quantity and qualities required by boiler constraints

There is a maximum supply quantity O_{jis}^{u} that can be purchased each month. Therefore, this constraint is developed as:

$$0 \leq z_{jis} \leq O_{jis}^{U} \tag{9}$$

The properties of biomass feedstock vary widely, and biomass fuels differ significantly from coal in terms of their physical and chemical properties, composition, and energy content. Most biomass fuels contain more volatile materials, more ash, less sulfur and nitrogen, less heating value, more moisture content, and have larger and a wider range of particle sizes. If the fuel blends to be burned do not meet the boiler requirements, they could adversely influence the co-firing process and possibly cause serious problems. Therefore, to ensure that the biomass and coal blends can be co-fired in the existing boilers, it is necessary to focus on the fuel blend characteristics. Let t be the fuel quality, $t=1$ be the volatile matter content, $t=2$ be the heat rate, $t=3$ be the ash content, $t=4$ be the moisture content, and $t=5$ be the sulfur content (Lv et al., 2016).

$$E\left[\tilde{LB}_t\right] \leq \frac{\sum_{i=1}^{I} E\left[\tilde{B}_{it}\right]x_{jis}}{\sum_{i=1}^{I} x_{jis}} \leq E\left[\tilde{UB}_t\right] \tag{10}$$

2.3.4. Technical constraint

Biomass fuels have much less carbon and a higher fraction of hydrogen and oxygen than coal, which means they have much less energy density; that is, a typical biomass has only about one tenth of the overall fuel density of coal. It has been found that co-firing with a certain percentage of biomass can improve the combustion efficiency of coal because of the enhanced ignition characteristics and the devolatilization in the volatile reaction region from the synergetic effects in biomass-coal co-firing (Agbor et al., 2014). Let 1-i_b be the biomass fuel and i_b-I be the coal fuel with UR being upper percent of biomass. Therefore, this constraint is written as:

$$\frac{\sum_{i=1}^{i_b} x_{jis}}{\sum_{i=1}^{I} x_{jis}} \leq UR \tag{11}$$

2.3.5. Social responsibility constraint

CPPs should not only pay attention to profits, but also attach great importance to social responsibility. Electricity is a necessity in people's modern life. As a member of society, each CPP enjoys social resources and in return is supposed to generate a certain amount of electric power owing to their capacities. Let U_{js} be the power needed to be generated in s month by CPP j.

$$\sum_{i=1}^{I} E\left[\tilde{C}_{ji}\right]x_{jis} \geq U_{js} \tag{12}$$

2.3.6. Carbon emissions quota constraint

As the relationship between the authority and the CPPs is a leader-follower relationship, the authority develops an appropriate carbon emissions quotas scheme. Situated on the lower level, the actual carbon emissions of each CPP cannot exceed the quotas. Set $\tilde{CE}_i$ as the carbon emissions caused by burning a unit of fuel i. Therefore the mathematical form is described as:

$$\sum_{s=1}^{S}\sum_{i=1}^{I} E\left[\tilde{CE}_{ji}\right]x_{jis} \leq y_j \tag{13}$$

2.3.7. Fuel resources storage constraints

As biomass is a renewable carbon dioxide neutral energy source that can potentially decrease pollutants, it has been seen as an attractive renewable fuel to supplement coal. However, biomass availability for power generation depends heavily upon the month. Therefore, a dynamic multi-stage model is needed to describe fuel resources storage. The CPPs must monitor their cumulative fuel resource storage quantities and adjust their fuel purchase strategies each month; the storage quantity at the terminal cannot be negative.

$$I_{jis} = I_{ji(s-1)} + z_{jis} - x_{jis} \tag{14}$$

$$0 \leq x_{jis} \leq z_{jis} + I_{ji(s-1)} \tag{15}$$

There is an also upper quantity restriction on the warehousing ability, set as I_j^M. CPPs are unable to store and buy beyond these restrictions; therefore storage quantity at the terminal in the previous month and the purchase quantity in the present month is confined as:

$$\sum_{i=1}^{I} I_{ji(s-1)} + \sum_{i=1}^{I} z_{jis} \leq I_j^U \tag{16}$$

2.4. Global model

A dynamic equilibrium strategy based bi-level multi-objective multistage decision making model is developed to address the relationship between the authority and CPPs, the trade-off between economic development and environmental protection, and biomass availability time conflicts. In the decision making system, the authority on the upper level, first makes an initial decision on carbon emissions allowances allocation to maximize revenue and minimize carbon emissions. With full knowledge of the authority's decision, CPPs attempt to maximize their profits and develop biomass-coal co-firing ratio schemes under the consideration of the fuel resource quantity and quality limitations, the technical constraint, carbon emissions allowance and social responsibility constraints. Then the CPPs feed back their decisions to the authority which updates carbon emissions allowances, after which CPPs reconsider biomass-coal co-firing ratio strategies and again feed back to the authority. From this interactive process, the global satisfactory solution is obtained. Therefore, from an integration of the constraints and objective functions as Eqs. (2)–(16), the full multi-objective bi-level dynamic model Eq. (17) is formulated as follows.

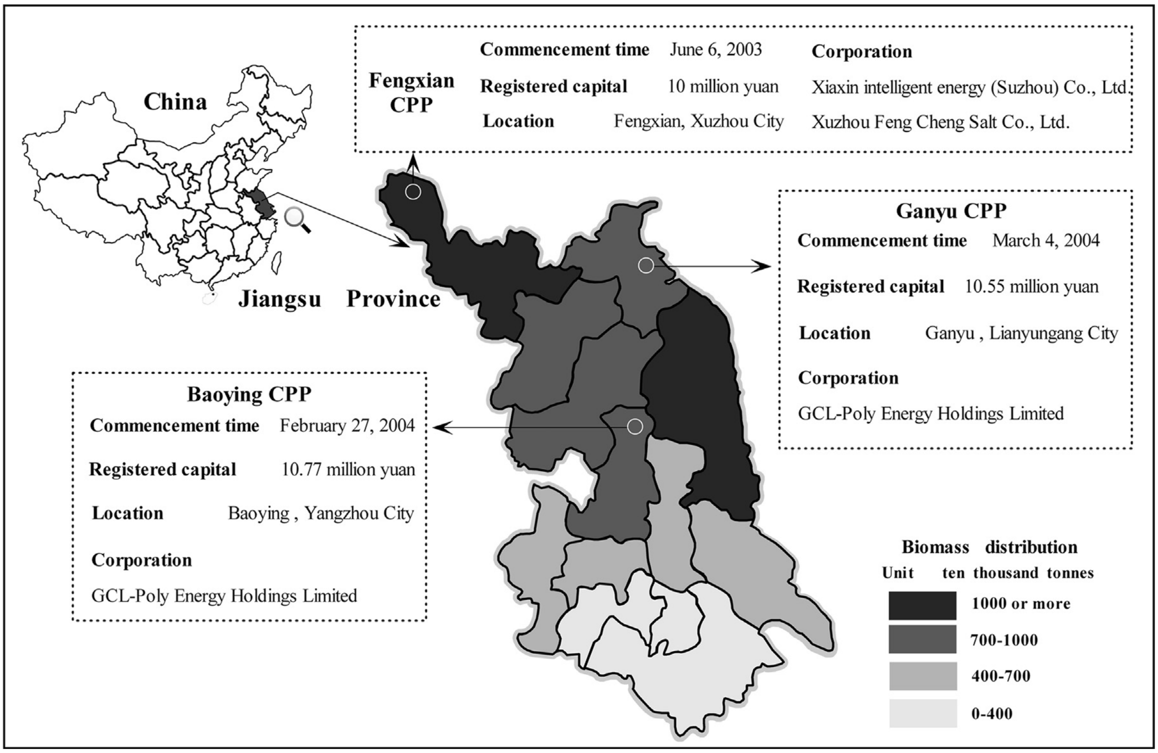


Fig. 2. Case region and CPP locations.

$$
\begin{aligned}
&\max F_1 = \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{i=1}^{I} MQE\left[\tilde{C}_{ji}\right]x_{jis} + \mathrm{u}\sum_{j=1}^{J} y_j\\
&\min F_2 = \sum_{j=1}^{J} y_j\\
&s.\,t.\begin{cases}
Q_j^L \le y_j \le Q_j^U\\
\sum\limits_{j=1}^{J} E\left[\tilde{H}_j\right]y_j \ge \sum\limits_{j=1}^{J}\sum\limits_{s=1}^{S} U_{js}\\
\dfrac{y_j - \sum_{s=1}^{S}\sum_{i=1}^{I} E\left[\tilde{CE}_{ji}\right]x_{jis}}{y_j} \le \lambda,\ \forall\, j \in \vartheta\\
\max f = Q\sum\limits_{s=1}^{S}\sum\limits_{i=1}^{I} E\left[\tilde{C}_{ji}\right]x_{jis} - \sum\limits_{s=1}^{S}\sum\limits_{i=1}^{I} E\left[\tilde{P}_{jis}\right]z_{jis} - Z\sum\limits_{s=1}^{S}\sum\limits_{i=1}^{I} I_{jis}\\
-\sum\limits_{s=1}^{S}\sum\limits_{i=1}^{I}\sum\limits_{k=1}^{p} E\left[\tilde{N}_{ik}\right]V_{jk}x_{jis} - MQ\sum\limits_{s=1}^{S}\sum\limits_{i=1}^{I} E\left[\tilde{C}_{ji}\right]x_{jis} - uy_j\\
s.\,t.\begin{cases}
\dfrac{\sum_{i=1}^{I} E\left[\tilde{B}_{it}\right]x_{jis} + \sum_{i=1}^{I} E[\tilde{\eta}_i]\left(1 - E\left[\tilde{B}_{it}\right]\right)x_{jis}}{\sum_{i=1}^{I} x_{jis}} \ge \alpha,\ \forall\, s \in \sigma\\
0 \le z_{jis} \le O_{jis}^U,\ \forall\, i \in \gamma,\ s \in \sigma\\
E\left[\tilde{LB}_t\right] \le \dfrac{\sum_{i=1}^{I} E\left[\tilde{B}_{it}\right]x_{jis}}{\sum_{i=1}^{I} x_{jis}} \le E\left[\tilde{UB}_t\right],\ \forall\, s \in \sigma,\ t \in \varsigma\\
\dfrac{\sum_{i=1}^{i_b} x_{jis}}{\sum_{i=1}^{I} x_{jis}} \le UR,\ \forall\, s \in \sigma\\
\sum\limits_{i=1}^{I} E\left[\tilde{C}_{ji}\right]x_{jis} \ge U_{js},\ \forall\, s \in \sigma\\
\sum\limits_{s=1}^{S}\sum\limits_{i=1}^{I} E\left[\tilde{CE}_{ji}\right]x_{jis} \le y_j\\
I_{jis} = I_{ji(s-1)} + z_{jis} - x_{jis},\ \forall\, i \in \gamma\\
0 \le x_{jis} \le z_{jis} + I_{ji(s-1)}\\
\sum\limits_{i=1}^{I} I_{ji(s-1)} + \sum\limits_{i=1}^{I} z_{jis} \le I_j^U,\ \forall\, s \in \sigma
\end{cases}
\end{cases}
\end{aligned}
\tag{17}
$$

The above bi-level dynamic multi-objective biomass-coal co-firing model is developed to ensure carbon emissions reductions in CPPs. Compared with previous biomass-coal co-firing models, this model considers the multiple decision makers and multiple conflicts, therefore it is suitable for actual production and can assist CPPs to make reasonable production schemes under the authority's policy. In this model, as β presents attitude of the authority towards carbon emissions reduction, and λ presents attitude of the authority towards the gap between the quota and the actual value, this model is flexible and robust. Under different circumstances, the authority has the ability to adjust the policy control parameters to achieve the most satisfactory results. This model is also practicable when the authority has full controlled over the CPPs. At that time, the relationship between the authority and CPPs is like a general corporation and its subsidiaries. Under the limited carbon emissions resources, the proposed model can also be used for the distribution of carbon emissions allowances by the general corporation to its subsidiaries (Lu et al., 2006).

3. Case study

3.1. Case description

China is entering a post-coal growth period that it holds the largest market of coal all over the world, and the coal consumption is projected to reach peak, accounting for nearly 50% of global coal consumption in 2035 along with numerous carbon emissions (Qi et al., 2016; Global, 2017b; Wang and Li, 2017; Zhang et al., 2017). Jiangsu Province, located in southeast China, (Fig. 2) is not only an economically prosperous province ranking second of all Chinese provinces, but also a populous province with an estimated 2016 population at more than 78.66 million. Because of the large population and its economic superiority, Jiangsu Province is a major carbon emitter in China at 20.3 million tonnes per annum. CPP is the most important end-user of coal, becoming the vital source for regional carbon emissions (Zhao et al., 2008). Therefore, Jiangsu authority are urgently seeking to reduce carbon emissions while maintaining economic growth. Under economic

Table 1
Agricultural bioenergy in Jiangsu province.

Crop straw								Forest biomass		Animal & human	Rural household
Wheat	Barley	Rice	Corn	Beans	Peanut	Rapeseed	Cotton	Switchgrass	Wood wastes	excreta	solid wastes
		✓							✓		

Note: ✓ means this kind of agricultural bioenergy is used in this case.

and environmental pressure, there is a push towards sustainable development with many policies being implemented that are aimed at developing cleaner and lower-carbon fuel sources. The Chinese government's Energy Development Strategy Action Plan aims to reduce coal's share to less than 62% of the energy mix by 2020 (Global, 2017a). Fortunately, as Jiangsu Province is rich in agricultural bioenergy (Table 1), as early as 2009, the province was producing an annual bioenergy output of about 40 million tonnes and had already considered biomass-coal co-firing to deal with the predicted rise in energy demand and to reduce carbon emissions (Zhang et al., 2013). Because of the abundant biomass resources in the north and center of Jiangsu Province, since 2003, several biomass-coal co-firing CPPs have been built. To reduce the computation burden, only three main biomass-coal co-firing CPPs are examined in this case: Fengxian CPP, Ganyu CPP and Baoying CPP (Fig. 2), all of which use straw(S), wood waste(W), and coal as fuel. As coal from different places has different properties, Yaoqiao coal(Y) and Zhangshuanghe coal(Z) are used in these CPPs.

3.2. Model transformation and solution approach

As Jiangsu Province requires further economic development, the authority gives top priority to revenue when making decisions; however, it also needs to consider environmental protection to ensure that the economy develops within its environmental carrying capacity. Let β be the attitude of the authority towards carbon emissions reduction. To seek the trade-off between revenue maximization and carbon emissions minimization, in this paper, the carbon emissions minimization objective is transformed into a constraint controlled within a range of acceptance (Lv et al., 2016). Therefore, Eq. (17) can be transformed as:

$$\max F = \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{i=1}^{I} MQE\left[\tilde{C}_{ji}\right]x_{jis} + \mathrm{u}\sum_{j=1}^{J} y_j$$
$$s.\ t.\ \begin{cases}\sum_{j=1}^{m} y_j \le \beta LCE\\ (x_{jis}, y_j, z_{jis}) \in R\end{cases} \tag{18}$$

where R is the feasible region formed by the Eqs. (4)–(16).

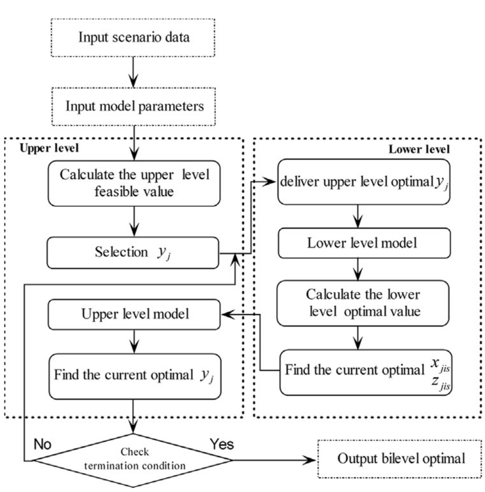
In this hierarchical optimization structure, the leader (the authority) and the followers (many CPPs) must optimize their own objectives by considering the objectives of the others. To resolve this linear bi-level programming problem, the following algorithm in Matlab 7.0 is used to determine an optimal solution. The purpose of this algorithm is to achieve equilibrium between economic development and environmental protection and to resolve the conflicts between the authority and the CPPs. First, the upper level authority's initial optimal solution for revenue maximization is determined. Then, this initial optimal upper level solution is put into the lower level model and an optimal solution calculated based on the lower-level objectives. Next, the results of the lower level model are fed back to the upper level model to determine the subsequent optimal solution. This process is repeated until an optimal solution to the bi-level programming is found (Lv et al., 2016). The procedure for this solution approach is shown in Fig. 3.

3.3. Data collection

The basic necessary data for Fengxian CPP, Ganyu CPP, and Baoying CPP are shown in Tables 2–7 and are divided into the fixed data and the uncertain data.

The fixed data shown in Tables 2, 4, 5 were taken from the White Paper on straw power generation project construction management in Jiangsu Province, the Jiangsu Province Statistical Yearbook, and the official CPP websites (Bureau, 2017). Tables 2, 4 show the requirements and responsibilities at the three main CPPs, the other needed parameters for the proposed model are shown in Table 5. The uncertain data collected from the Jiangsu Province Statistical Yearbook and the official websites of each CPP are shown in Tables 3, 6, 7. Table 3 shows straw price over 12 months, Table 6 shows the fuel characteristics of the various bunkers, and Table 7 gives the boiler requirements at the three main CPPs.

As Jiangsu Province is a relatively developed region, carbon emissions quota allocation satisfaction and regional fairness are paramount. Therefore, the control parameter λ is set at 0, indicating that the authority has a strict attitude towards the gap between the quota and the actual value.



Step 1: Find the feasible region of the upper level model

Step 2: Randomly choose y_j^1 in the range.

Step 3: Input the initial y_j^1 into the lower level model.

Step 4: Calculate the optimal solution x_{jis}^1 of the lower level model.

Step 5: Feedback x_{jis}^1 into the upper level model.

Step 6: Calculate the optimal solution y_j^2 for the upper level model and transmit its result to the lower level model.

Step 7: Repeat Step 4, Step 5 and Step 6 until $\frac{\left|y_j^q - y_j^{q-1}\right|}{y_j^{q-1}} \le 1\%$.

Fig. 3. Algorithmic flowchart.

Table 2
Straw resource quantities, prices, and power demand.

Month	Fengxian CPP		Ganyu CPP		Baoying CPP	
	Quantity: O_{jis}^U (10^4 tonnes)	Power: U_{js} (10^7 kW h)	Quantity: O_{jis}^U (10^4 tonnes))	Power: U_{js} (10^7 kW h)	Quantity: O_{jis}^U (10^4 tonnes)	Power: U_{js} (10^7 kW h)
1	4.2	22.4	0.6	10.07	0.6	14.47
2	3.7	15.24	1.1	5.8	0.9	8.46
3	11.7	21.56	1.4	8.61	1.2	13.1
4	18.5	20.26	2	7.97	2	12.52
5	29.6	21.97	81.9	9.07	92.9	13.3
6	116.5	22.3	91.3	9.38	95.9	13.44
7	38.2	25.23	19.9	11.06	65.7	16.78
8	36.8	23.26	28.7	9.93	34.3	15.18
9	177.5	16.61	142.3	7.36	132.6	9.67
10	77.2	17.34	58.2	7.98	60.2	11.28
11	22.1	21.5	9.5	10.82	11.3	13.64
12	10.3	22.57	1.3	11.95	1.7	14.78

Table 3
Fuzzy straw prices.

Month	Fengxian CPP price: $\tilde{P}_{jis}$ (CNY/tonne)	Ganyu CPP price: $\tilde{P}_{jis}$ (CNY/tonne)	Baoying CPP price: $\tilde{P}_{jis}$ (CNY/tonne)
1	(715,725,735,740)	(725,730,740,750)	(727,732,748,755)
2	(710,720,730,740)	(690,695,705,710)	(720,725,735,740)
3	(705,715,725,735)	(670,675,680,685)	(710,715,720,725)
4	(690,695,700,705)	(670,680,690,705)	(685,695,705,710)
5	(663,670,676,685)	(625,630,640,645)	(565,570,575,580)
6	(630,635,640,650)	(590,598,606,615)	(528,535,543,650)
7	(640,645,656,660)	(633,638,645,650)	(630,635,640,645)
8	(630,635,645,650)	(620,626,632,638)	(655,660,665,670)
9	(665,675,685,790)	(577,585,594,600)	(580,590,600,610)
10	(615,620,630,635)	(615,620,625,631)	(620,635,645,660)
11	(645,655,665,670)	(652,657,665,670)	(675,685,695,700)
12	(705,710,720,730)	(690,695,705,710)	(710,715,720,725)

Table 4
Crisp parameters.

	Fengxian CPP	Ganyu CPP	Baoying CPP
Least carbon emissions: Q_j^L (tonnes)	5.76×10^6	4.67×10^6	6.47×10^6
Utmost carbon emissions: Q_j^U (tonnes)	1.05×10^7	1.034×10^7	1.13×10^7
Max storage ability: I_j^U (tonnes)	7.85×10^5	5.91×10^5	6.15×10^5
Procurement price: V_k (CNY/kg)			
For SO_2	1.8	2	2.2
For NO_x	14.4	14.7	14.5

Table 5
Other parameters.

Carbon emissions quota price: u (CNY/tonne)	30
Value-added tax: S (%)	1
Price of unit electric: Q (CNY/kW h)	0.45
Amount of power needed in a region: U (kW h)	5.1686×10^9
Upper percentage of biomass in fuel blend: UR	0.1
Storage price monthly per unit: K (CNY/10^4 tonnes)	0.125
Carbon emissions last year: LCE(tonnes)	2.37×10^7

4. Results and discussion

4.1. Results under different scenarios

The results under various scenarios are given in this section. As Eq. (8) indicates, combustion efficiency α is restrained by violate matter and burn-out fraction of char. Based on the collected data, α can vary from 0.42 to 0.49; however, the variation range for α is a little smaller due to the power demand and carbon emissions quota constraints. To examine and verify the variation range for α, β was set at 1 and then Matlab was used to calculate the results, from which it was found that when α changes from 0.43 to 0.44 the results of the proposed model were acceptable. Therefore, three scenarios are presented to demonstrate the effectiveness of the model. In each scenario, β which represents the attitude towards carbon emissions reduction is set to change from 1 to 0.75, with the lower β indicating the stricter attitude. The model is also calculated without carbon emissions constraint for comparison.

Scenario 1 is shown in Table 8, in which α is fixed at 0.44 and β changes from 1 to 0.75. In Scenario 2 in Table 9, α is fixed at 0.435 and β changes from 1 to 0.75. In scenario 3 in Table 10 α is fixed at 0.43 and β changes from 1 to 0.75. Based on these results, the following conclusions are drawn. First, as β reduces, revenue, the total carbon emissions and CPPs profits reduce. When β reduces, this indicates that the authority has a stricter attitude towards carbon emissions, and consequently the total carbon emissions reduce. Under the reduced limited carbon emissions resources, CPPs generate less power and earn less profits. Revenue also reduce as tax and carbon emissions allowances fees from CPPs become less. Second, if environmental protection is absent, the CPPs are able to generate as much power as possible, emit carbon dioxide under full-load production, and earn larger profits. And there is greater revenue for the authority and higher total carbon emissions. Last, even though the CPP profits vary with combustion efficiency, the carbon emissions allowances do not. The reason for this is that the combustion efficiency changes the biomass-coal co-firing ratios, which in turn impact profits. However, as the combustion

Table 6
Fuzzy uncertain parameters for each fuel.

	Straw	Wood waste	Yaoqiao coal	Zhangshuanghe coal
Fuel properties: $\tilde{B}_{it}$				
Volatile matter (wt%)	(64.2,64.7,65.4,65.9)	(44.7,45.03,45.32,45.6)	(25.5,25.8,26.2,26.5)	(31.6,31.9,32.2,32.5)
Heat rate (Gj/tonne)	(19.3,19.6,20.2,20.9)	(18.35,18.7,19.1,19.81)	(27.8,28.2,28.55,28.8)	(21.8,22.2,22.75,23.1)
Ash content(wt%)	(27.28,28.07,28.4,28.88)	(19.76,20,20.4,20.56)	(8.86,9.1,9.5,9.8)	(19,19.3,19.7,20)
Moisture content (wt%)	(12.5,12.8,13.2,13.5)	(8.6,8.93,9.2,9.55)	(6.75,6.9,7.2,7.4)	(4.6,4.8,5.22,5.45)
Sulfur content (wt%)	(0.17,0.18,0.21,0.24)	(0.09,0.1,0.12,0.14)	(0.33,0.4,0.47,0.52)	(0.59,0.62,0.66,0.69)
Pollutants emission factor: $\tilde{E}_{ik}$ (kg/tonne)				
For SO_2	(1.5,1.8,2.13,2.4)	(3.95,4.1,4.4,4.72)	(2.7,3,3.35,3.7)	(8.25,8.6,8.9,9.2)
For NO_x	(4.6,4.8,5.1,5.34)	(0.92,1.1,1.3,1.45)	(9.34,9.6,9.86,10.2)	(9.9,10.2,10.52,10.7)
Char burn-out fraction: $\tilde{\eta}_i$ (%)	(44,48,52,56)	(36,38,40,43)	(17,19,21,23)	(17,20,22,24)

Table 7
Fuzzy CPP requirements and factors.

	Fengxian CPP		Ganyu CPP		Baoying CPP	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Volatile matter (wt%)	(5.5,5.9,6.2,6.6)	(35.9,36.2,36.5,36.9)	(7.1,7.3,7.6,7.8)	(37.6,37.9,38.1,38.4)	(8.7,8.9,9.2,9.4)	(38.6,38.8,39,39.3)
Heat rate (Gj/tonne)	(20.9,21.3,21.6,21.9)	–	(21.6,21.9,22.1,22.4)	–	(21.4,21.7,21.9,22.1)	–
Ash content (wt%)	–	(25.6,26,26.3,26.5)	–	(27.7,27.9,28.2,28.4)	–	(28.6,29,29.2,29.5)
Moisture content (wt%)	–	(8.6,8.9,9.1,9.4)	–	(9.6,9.9,10.1,10.4)	–	(12.6,12.9,13.2,13.7)
Sulfur content (wt%)	–	(0.91,0.96,0.99,1.15)	–	(1.1,1.3,1.8,2.2)	–	(1.7,1.9,2.2,2.5)
Carbon emissions $\tilde{CE}_{ji}$ (kg/tonne)						
Straw	(1375,1500,1600,1750)		(1200,1350,1500,1650)		(1350,1400,1500,1600)	
Wood waste	(1700,1850,2070,2290)		(1750,1900,2000,2150)		(1350,1500,1700,1850)	
Yaoqiao coal	(2325,2450,2500,2600)		(2125,2350,2500,2630)		(2250,2300,2450,2600)	
Zhangshuanghe coal	(1970,2030,2070,2100)		(2150,2200,2375,2450)		(2150,2250,2300,2400)	
Fuel to power $\tilde{C}_{ji}$ (kW h/tonne)						
Straw	(1250,1400,1550,1700)		(1500,1650,1850,1950)		(1300,1500,1700,1900)	
Wood waste	(1550,1700,1900,2050)		(1450,1650,1870,2090)		(1200,1400,1550,1750)	
Yaoqiao coal	(2050,2200,2350,2500)		(2100,2200,2350,3450)		(2200,2300,2450,2550)	
Zhangshuanghe coal	(1950,2100,2250,2350)		(1900,2050,2130,2250)		(2010,2150,2300,2450)	
Carbon to power $\tilde{H}_j$ (kW h/tonne)	(935,945,955,965)		(1003,1007,1013,1016)		(960,966,978,993)	

efficiency does not change the maximum acceptable total carbon emissions, the carbon emissions allowances remain the same.

4.2. Propositions and analyses

In this section, the results under diverse scenarios (Tables 8–10) are discussed.

Proposition 1. A dynamic equilibrium strategy based biomass-coal co-firing method can result in carbon emissions reductions.

This paper proposes a dynamic equilibrium strategy based biomass-coal co-firing method. As can be seen in Fig. 4, which gives a visual representation of carbon emissions, biomass-coal co-firing method has a significant effect on reducing carbon emissions. From the results shown in Tables 8–10, β which represents the authority's attitude towards

Table 8
Results when α = 0.44 and β is changing.

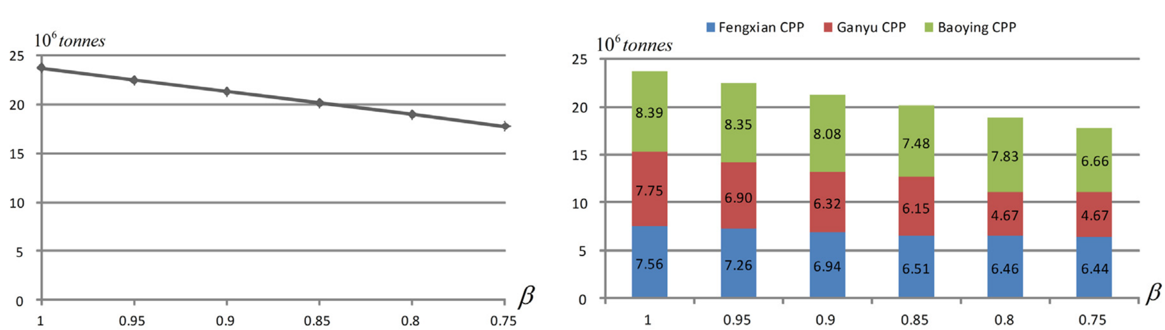
	The authority	Fengxian CPP		Ganyu CPP		Baoying CPP	
	Revenue (CNY)	Profits (CNY)	Carbon emissions allowances (tonnes)	Profits (CNY)	Carbon emissions allowances (tonnes)	Profits (CNY)	Carbon emissions allowances (tonnes)
β = 1	824,124,154	4,451,759,826	7,560,926	4,168,156,720	7,746,840	4,436,308,120	8,392,234
β = 0.95	783,256,321	4,306,500,002	7,261,291	3,726,845,015	6,899,931	4,419,829,892	8,353,778
β = 0.9	742,526,138	4,148,066,003	6,935,241	3,421,066,080	6,318,592	4,298,714,817	8,076,167
β = 0.85	701,780,815	3,939,222,482	6,509,867	3,332,479,147	6,150,287	3,993,437,743	7,484,847
β = 0.8	660,556,261	3,914,166,707	6,459,159	2,554,275,247	4,674,309	4,170,160,156	7,826,532
β = 0.75	619,531,368	3,906,769,677	6,444,189	2,552,713,223	4,671,356	3,566,293,572	6,659,454
No carbon emission constraint	837,332,385	4,603,086,052	7,875,000	4,133,640,676	7,755,000	4,471,773,541	8,475,000

Table 9
Results when $\alpha = 0.435$ and β is changing.

	The authority	Fengxian CPP		Ganyu CPP		Baoying CPP	
	Revenue (CNY)	Profits (CNY)	Carbon emissions allowances (tonnes)	Profits (CNY)	Carbon emissions allowances (tonnes)	Profits (CNY)	Carbon emissions allowances (tonnes)
$\beta = 1$	824,017,103	4,454,356,818	7,560,926	4,183,966,990	7,746,840	4,452,589,908	8,392,234
$\beta = 0.95$	783,123,956	4,309,906,907	7,261,291	3,739,566,760	6,899,931	4,436,072,652	8,353,778
$\beta = 0.9$	742,550,083	4,152,222,662	6,935,241	3,432,827,618	6,318,592	4,316,834,319	8,076,167
$\beta = 0.85$	701,798,004	3,944,814,098	6,509,867	3,343,889,217	6,150,287	4,017,184,370	7,484,847
$\beta = 0.8$	660,588,047	3,919,885,299	6,459,159	2,562,826,418	4,674,309	4,194,894,359	7,826,532
$\beta = 0.75$	619,548,106	3,912,525,755	6,444,189	2,561,258,417	4,671,356	3,587,622,374	6,659,454
No carbon emission constraint	837,640,608	4,604,992,957	7,875,000	4,162,462,747	7,755,000	4,488,139,326	8,475,000

Table 10
Results when $\alpha = 0.43$ and β is changing.

	The authority	Fengxian CPP		Ganyu CPP		Baoying CPP	
	Revenue (CNY)	Profits (CNY)	Carbon emissions allowances (tonnes)	Profits (CNY)	Carbon emissions allowances (tonnes)	Profits (CNY)	Carbon emissions allowances (tonnes)
$\beta = 1$	823,832,277	4,454,356,817	7,560,926	4,196,291,295	7,746,840	4,466,603,158	8,392,234
$\beta = 0.95$	783,005,652	4,309,906,906	7,261,291	3,751,866,731	6,899,931	4,450,064,080	8,353,778
$\beta = 0.9$	742,436,605	4,152,222,660	6,935,241	3,444,181,222	6,318,592	4,330,668,228	8,076,167
$\beta = 0.85$	701,851,371	3,944,814,099	6,509,867	3,354,888,571	6,150,287	4,040,413,096	7,484,847
$\beta = 0.8$	660,654,846	3,919,885,301	6,459,159	2,570,950,912	4,674,309	4,219,174,655	7,826,532
$\beta = 0.75$	619,629,466	3,912,525,758	6,444,189	2,557,310,004	4,671,356	3,608,335,619	6,659,454
No carbon emission constraint	837,639,036	4,604,992,957	7,875,000	4,181,655,784	7,755,000	4,502,188,550	8,475,000



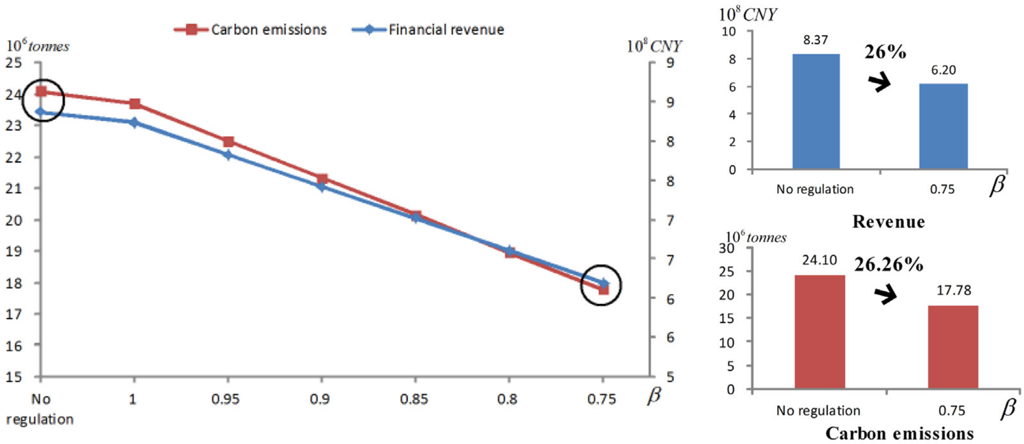
(a) Total carbon emissions. (b) CPP carbon emissions.

Fig. 4. Carbon emissions under different β values.

carbon emissions reductions, can be adjusted to the lowest potential carbon emissions level of 0.75. This clearly shows that the dynamic equilibrium strategy based biomass-coal co-firing method has the potential to reduce carbon emissions by about 25% compared with the carbon emissions from the previous production period. In the proposed model, a dynamic equilibrium strategy based biomass-coal co-firing method is employed, in which the authority allocates carbon emissions quotas to multiple subordinate CPPs, with higher allocations being given to the CPPs that have better carbon emissions reductions performance. When CPPs are allocated limited carbon emissions quota, to gain greater carbon emissions allocations, they need to adjust their biomass-coal co-firing ratios and develop fuel purchase schemes that improve their carbon emissions reduction performance. Therefore, the dynamic equilibrium strategy based biomass-coal co-firing method can reduce carbon emissions.

Proposition 2. A lack of environmental protection constraints brings about damage to sustainable development.

From Fig. 5, when there are no environmental protection constraints, the carbon emissions are larger. For example, when $\alpha = 0.44$, if there is no environmental protection, the authority receives 26% higher revenue; however, extra 26.26% carbon dioxide is emitted into the atmosphere; that is, 26% revenue increase is paid for 26.26% carbon emissions increase. In this situation, all CPPs seek to generate as much power as they can to gain the greatest profits. Because they are allowed to emit a large amount of carbon dioxide, they are levied higher tax and higher carbon emissions allowances fees, which increases the authority's revenue. Similar situation can be seen in Tables 9, 10. Therefore, it can be concluded that when there is no environmental protection constraint, although revenue increases, this is at the expense of increased carbon dioxide emissions, which is harmful to



(a) Under different β values (b) Comparative analysis

Fig. 5. Revenue and carbon emissions when $\alpha = 0.44$.

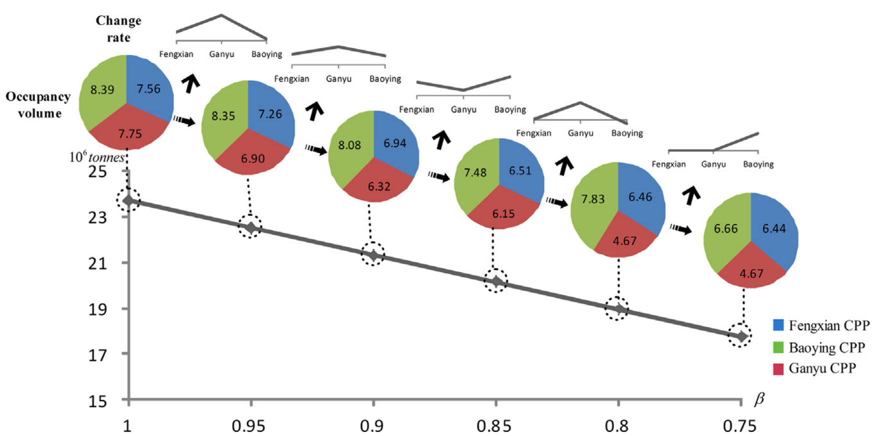


Fig. 6. Carbon emissions under different β values.

sustainable development.

Proposition 3. Different CPPs have different sensitivities under different environmental protection constraints.

From Fig. 6, it can be seen that the CPPs have different sensitivities towards the changing carbon emissions constraints. For example, when β changes from 1 to 0.95, the carbon emissions allowances reduce at all three CPPs; Fengxian CPP by 29.96 thousand tonnes, Ganyu CPP by 84.69 thousand tonnes, and Baoying CPP by 3.84 thousand tonnes. As the reduction ratios are usually different, the carbon emissions allowances are respectively reduced by 4%, 10.9% and 0.5%. Therefore, Ganyu CPP has an advantage over the other two CPPs when competing for carbon emissions allowance. Similar situations take place when β changes from 0.95 to 0.9, and from 0.85 to 0.8. However, when β varies from 0.9 to 0.85, the carbon emission allowances the three CPPs receive are respectively reduced by 6.1%, 2.7% and 7.3%, which means that Baoying CPP has an advantage over the other two CPPs in competing for carbon emissions allowance. Similar situation can also be seen when β varies from 0.8 to 0.75. We can figure out from Eq. (5) that the CPP with higher $\tilde{E}_j$, exactly as Ganyu CPP and Baoying CPP, has high power generation and low carbon emissions and is preferred to be allocated higher carbon emissions allowance by the authority.

Proposition 4. The marginal carbon emissions reduction rate is a slightly larger than revenue when the carbon emissions constraint is stricter.

From Fig. 7, it can be seen that both revenue and the total carbon emissions both decrease when the carbon emissions constraints are stricter. However, the marginal carbon emissions reduction rate is a bit larger than that of revenue. When the authority has a relatively relaxed attitude towards carbon emissions reduction ($\beta = 0.8$), the total carbon emissions allowance is 18.96 million tonnes and revenue is 660.56 million CNY. When the authority has the strictest attitude ($\beta = 0.75$), the total carbon emissions reduce to 17.775 million tonnes and revenue reduces to 619.53 million CNY; that is, the total carbon emissions decrease by 6.7% and the revenue decreases by 6.6%. Similar results can also be seen in other situations, as shown in Tables 9, 10. Therefore, it can be inferred that although a relatively stricter environmental protection decreases revenue, it would result in less carbon emissions and greater benefits to the environment.

Proposition 5. Combustion efficiency does not significantly affect CPP profits.

From Tables 8–10, it can be seen that when the combustion efficiency increases, there is little effect on CPP profits. When $\beta = 1$ and $\alpha = 0.43$, profits at the Fengxian CPP, Ganyu CPP, and Baoying CPP are respectively 4.454, 4.196 and 4.466 billion CNY. When β remains unchanged and α increases to 0.435, profits reduce to 4.454, 4.183 and 4.452 billion CNY. As α increases again to 0.44, profits decrease to 4.451, 4.168 and 4.436 billion CNY. Similar situation can be seen in Fig. 8 (b)–(f). The reason is that combustion efficiency does not change the carbon emissions allowances which are the key factors influencing profits. It just impacts biomass-coal co-firing ratio and slightly effects profits. Therefore, CPPs would be willing to sacrifice a small fall in profits to improve combustion efficiency and reduce emissions.

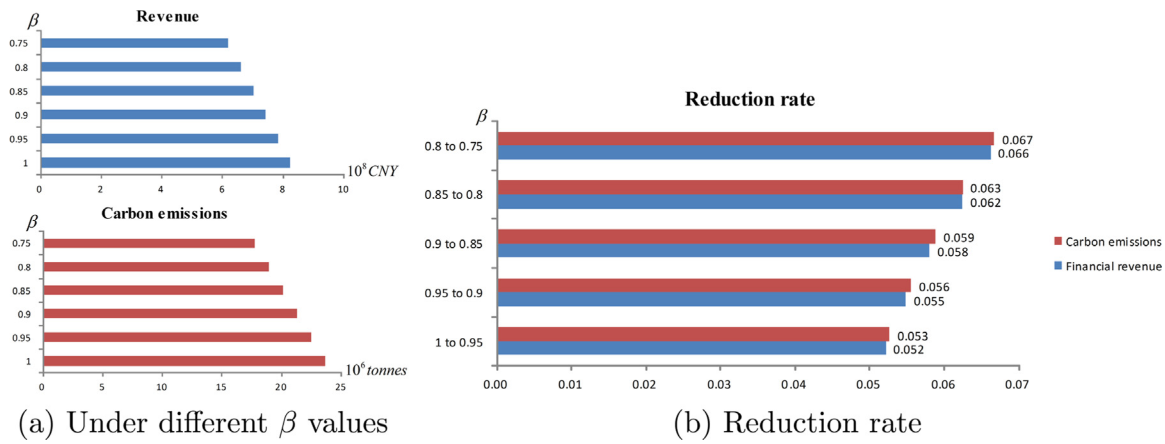


Fig. 7. Revenue and carbon emissions when α = 0.44 and β is changing.

4.3. Policy implications

Based on the above discussions and analyses, in this section, some policy implications are given.

(1) A carbon emissions allocation competition mechanism should be established.

To ensure carbon emissions reductions, a carbon emissions allocation competition mechanism that involves the authority and multiple CPPs is recommended, in which carbon emissions allowances allocation is the strategic point. The authority allocates carbon emissions allowances to subordinate CPPs based on their feedbacks,

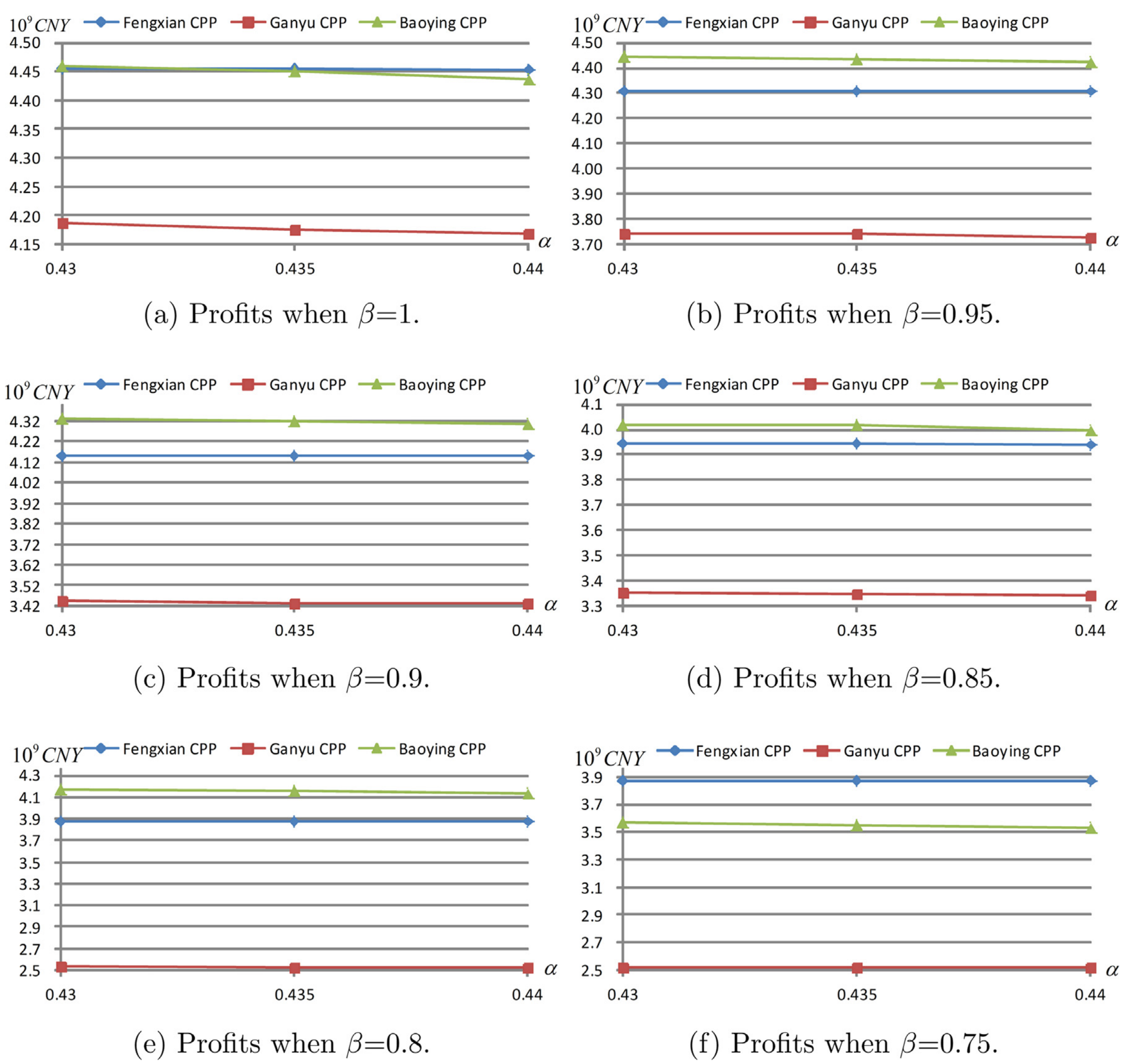


Fig. 8. Carbon emissions under different β values and α is changing.

following which each CPP develops the biomass-coal co-firing ratio scheme to ensure environmentally friendly power generation. As discussed in Proposition 1, the authority would allocate more carbon emissions allowances to the CPP which has better carbon emissions reduction performances. Under these limited carbon emissions quotas, the CPPs compete with each other to acquire more carbon emissions allowance. Therefore, with mechanism, it is easy to achieve lower carbon emissions. The carbon emissions allocation competition mechanism has an advantage over C&T in easy accessibility as with C&T transaction procedures is complicated and transaction costs is high. Meanwhile, this mechanism can bring about more significant carbon emissions reductions than carbon tax. More importantly, this mechanism can motivate all the CPPs to move toward cleaner production by competition. Therefore, a carbon emissions allocation competition mechanism is put forward to reduce the total carbon emissions from the CPPs and develop a cooperative relationship between the authority and the CPPs.

(2) A flexible attitude towards environmental protection should be taken.
It is recommended that the authority should choose a flexible carbon emissions reduction attitude based on the economic development level. The authority should take the actual situation into consideration and choose an optimal environmental protection attitude. As discussed in Propositions 2 and 4, if there were no carbon emissions constraints, the authority would receive higher revenue, which would be paid for by higher carbon emissions and would result in greater environmental damage. Therefore, when the economy is in relatively bad condition, the authority could adopt a more relaxed attitude towards environment protection to encourage greater economic development. However, after a period of time, as the economic developed, the authority could have a stricter attitude; that is, in subsequent periods, they can gradually tighten the policy control parameter until the strictest requirements are achieved. In this way, harmony between the economy-society-ecology system is guaranteed and sustainable development is realized.

(3) A gradual growth in combustion efficiency should be encouraged.
Combustion efficiency is of significant importance for energy conservation and emissions reductions. In this paper, combustion efficiency is limited by volatile matter and the extent of char combustion in biomass-coal co-firing method. To achieve high combustion efficiency, greater quantities of biomass are required, which is greatly beneficial to the environment. As discussed in Proposition 5, high combustion efficiency just incurs little losses in CPP profits, which can be accepted by CPPs and wouldn't destroy the cooperative relationship between the authority and CPPs. As a result, a gradual growth in combustion efficiency is recommended to better protect the environment.

5. Conclusions and future study

With a focus on reducing CPP carbon emissions, in this paper, a dynamic equilibrium strategy under a fuzzy environment was proposed based on a leader-follower decision process that considered the economic development and environmental protection trade-off, the relationship between the authority and the CPPs, and time conflict associated with biomass availability. Using this method, a carbon emissions allocation competition mechanism involving the authority and CPPs was established, in which the authority allocated the carbon emissions allowances to each CPP, following which the CPPs independently optimized their biomass-coal co-firing ratio decisions considering the biomass availability time conflict. The results from case study demonstrated the practicality and efficiency of the model in reducing carbon emissions. Sensitivity analyses under different scenarios were conducted, from which important conclusions were derived. (1) the dynamic equilibrium strategy based biomass-coal co-firing method was able to achieve carbon emissions reductions; (2) no environmental protection constraints leads to damage to sustainable development; (3) different CPPs have different sensitivities to changing carbon emissions reduction constraints; (4) when environmental protection is stricter, the carbon emissions reduction ratio is a slightly larger than the revenue; and (5) combustion efficiency does not significantly affect CPP profits.

In future research, the proposed method could be improved to consider other pollutants for complete environmental protection. In addition, this paper only considered two stakeholders (the authority and the CPPs) while other stakeholders such as community groups and international organizations were neglected. In the future, a more comprehensive method including more pollutants and additional stakeholders should be developed.

Acknowledgements

This work is supported by State Key Development Program of (for) Basic Research of China (973 Program, Grant no. 2011CB201200), the Funds for Creative Research Groups of China (Grant no. 50221402).

Appendix A. Notations

Indices	Description
i	Fuel index, $i \in \gamma = 1, 2, ..., i_b, ..., I$.where 1-$i_b$ represent biomass fuel, i_b-n represent coal fuel.
j	CPP index, $j \in \vartheta = 1, 2, ..., J$.
k	Pollutant index, $k \in \psi = 1, 2, ..., K$.
t	Fuel quality index, $t \in \varsigma = 1, 2, ..., T$.
s	Month index, $s \in \sigma = 1, 2, ..., S$.
Fixed parameter	**Description**
u	Price of per unit carbon emissions quota.
Q	Price of per unit of electric power.
M	Value-added tax that the authority levies on the CPPs.
O_{jis}^U	Max obtainable amount of fuel i in s month.
LB_t, UB_t	Lower and upper bounds for quality t of blended fuel to meet boilers' requirements.
U_{js}	Amount of power needed to be generated in s month by CPP j.
UR	Upper percent of biomass in blended fuel considering boilers' security.
Q_j^L, Q_j^U	Lower and upper bounds for the annual carbon emissions CPP j can carry.
V_{jk}	Unit operating costs to reduce pollutant k in CPP j.
Z	Storage price monthly per unit.
I_j^U	Upper storage ability of CPP j.

I_{jis}	Inventories of fuel i at the end of s month for CPP j.
LCE	Actual carbon emissions last year.
Uncertain parameters	**Description**
$\tilde{H}_j$	Conversion parameters for per unit of carbon emissions to power for CPP j.
$\tilde{P}_{jis}$	Unit purchasing price of fuel i in s month for CPP j.
$\tilde{C}_{ji}$	Conversion parameters from a unit of fuel i to power in CPP j.
$\tilde{N}_{ik}$	Amount of pollutant emissions k caused by burning a unit of fuel i.
$\tilde{CE}_{ji}$	Carbon emissions caused by burning a unit of fuel i in CPP j.
$\tilde{B}_{it}$	Quality t of fuel i.
$\tilde{\eta}_i$	Burn-out fraction of fuel i char.
Policy control parameters	**Description**
β	Attitude of the authority towards carbon emissions reduction.
λ	Attitude of the authority towards the gap between the quota and actual value.
α	Combustion efficiency.
Decision variables	**Description**
x_{jis}	Amount of fuel i used in s month for CPP j.
z_{jis}	Amount of fuel i bought in s month for CPP j.
y_j	Annual carbon emissions allocation quota for CPP j allocated by the authority.

References

Agbor, E., Zhang, X., Kumar, A., 2014. A review of biomass co-firing in North America. Renew. Sustain. Energy Rev. 40, 930–943.

Al-Mansour, F., Zuwala, J., 2010. An evaluation of biomass co-firing in Europe. Biomass Bioenergy 34 (5), 620–629.

Allen, J., Browne, M., Hunter, A., Boyd, J., Palmer, H., 1998. Logistics management and costs of biomass fuel supply. Int. J. Phys. Distrib. Log. 28 (6), 463–477.

Basu, P., 1999. Combustion of coal in circulating fluidized-bed boilers: a review. Chem. Eng. Sci. 54 (22), 5547–5557.

Basu, P., Butler, J., Leon, M.A., 2011. Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. Renew. Energy 36 (1), 282–288.

Baxter, L., 2005. Biomass-coal co-combustion: opportunity for affordable renewable energy. Fuel 84 (10), 1295–1302.

Beagle, E., Belmont, E., 2016. Technoeconomic assessment of beetle kill biomass co-firing in existing coal fired power plants in the western united states. Energy Policy 97, 429–438.

Broek, R.V.D., Faaij, A., Wijk, A.V., 1996. Biomass combustion for power generation. Biomass Bioenergy 11 (4), 271–281.

Bureau, J.S., 2017. ⟨http://tj.jiangsu.gov.cn/col/col4009/index.html⟩.

Chen, Z.M., Liu, Y., Qin, P., Zhang, B., Lester, L., Chen, G., Guo, Y., Zheng, X., 2015. Environmental externality of coal use in China: welfare effect and tax regulation. Appl. Energy 156, 16–31.

Colson, B., Marcotte, P., Savard, G., 2007. An overview of bilevel optimization. Ann. Oper. Res. 153 (1), 235–256.

Dai, C., Cai, X.H., Cai, Y.P., Huang, G.H., 2014. A simulation-based fuzzy possibilistic programming model for coal blending management with consideration of human health risk under uncertainty. Appl. Energy 133 (10), 1–13.

Dumortier, J., 2013. Co-firing in coal power plants and its impact on biomass feedstock availability. Energy Policy 60 (5), 396–405.

Eksioglu, S.D., Karimi, H., 2014. An Optimization Model in Support of Biomass Co-firing Decisions in Coal Fired Power Plants. Springer International Publishing.

Global, B., 2015. Bp Energy Outlook.

Global, B., 2017a. Bp Energy Outlook.

Global, B., 2017b. Bp Satistical Review of World Energy.

Global, B., 2018. Bp Energy Outlook.

Goto, K., Yogo, K., Higashii, T., 2013. A review of efficiency penalty in a coal-fired power plant with post-combustion CO_2 capture. Appl. Energy 111 (11), 710–720.

Grubb, M., 2012. Cap and trade finds new energy. Nature 491 (7426), 666–667.

Hubweber, L., Schmitt, M., Joly, D., Schmitt, M., 2001. Co-firing of coal and biomass fuel blends. Prog. Energy Combust. 27 (2), 171–214.

Keohane, N.O., 2009. Cap and trade, rehabilitated: using tradable permits to control U.S. greenhouse gases. Rev. Environ. Econ. Policy 3 (1), 42–62.

Li, J., Brzdekiewicz, A., Yang, W., Blasiak, W., 2012. Co-firing based on biomass torrefaction in a pulverized coal boiler with aim of 100% fuel switching. Appl. Energy 99 (6), 344–354.

Li, S., Xu, T., Hui, S., Wei, X., 2009. NO_x emission and thermal efficiency of a 300 mwe utility boiler retrofitted by air staging. Appl. Energy 86 (9), 1797–1803.

Li, Y., 2012. Dynamics of clean coal-fired power generation development in China. Energy Policy 51 (6), 138–142.

Lin, B., Li, X., 2011. The effect of carbon tax on per capita CO emissions. Energy Policy 39 (9), 5137–5146.

Liu, X., Chen, M., Wei, Y., 2016. Assessment on oxygen enriched air co-combustion performance of biomass/bituminous coal. Renew. Energy 92, 428–436.

Liu, Z., Guan, D., Wei, W., Davis, S.J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 524 (7565), 335.

Low, J., Cheng, B., Yu, J., 2017. Surface modification and enhanced photocatalytic CO_2 reduction performance of TiO_2: a review. Appl. Surf. Sci. 392, 658–686.

Lu, J., Shi, C., Zhang, G., 2006. On Bilevel Multi-follower Decision Making: General Framework and Solutions. Elsevier Science Inc.

Lv, C., Xu, J., Xie, H., Zeng, Z., Wu, Y., 2016. Equilibrium strategy based coal blending method for combined carbon and PM_{10} emissions reductions. Appl. Energy 183, 1035–1052.

Mallick, D., Mahanta, P., Moholkar, V.S., 2017. Co-gasification of coal and biomass blends: chemistry and engineering. Fuel 204, 106–128.

Mao, X.Q., Zeng, A., Hu, T., Xing, Y.K., Zhou, J., Liu, Z.Y., 2014. Co-control of local air pollutants and CO_2 from the Chinese coal-fired power industry. J. Clean. Prod. 67 (67), 220–227.

Moon, C., Sung, Y., Ahn, S., Kim, T., Choi, G., Kim, D., 2013. Effect of blending ratio on combustion performance in blends of biomass and coals of different ranks. Exp. Therm. Fluid Sci. 47 (5), 232–240.

Narayanan, K.V., Natarajan, E., 2007. Experimental studies on cofiring of coal and biomass blends in India. Renew. Energy 32 (15), 2548–2558.

Olivier, J., Janssens-Maenhout, G., Muntean, M., Peters, J., 2015. Trends in Global CO_2 Emissions: 2015 Report.

Pain, S., 2017. Power through the ages. Nature 551, 134–137.

Programme, U., 2017. Towards a Pollution-Free Planet.

Qi, Y., Stern, N., Wu, T., Lu, J., Green, F., 2016. China's post-coal growth. Nat. Geosci. 9, 564–566.

Rentizelas, A.A., Tolis, A.J., Tatsiopoulos, I.P., 2009. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew. Sustain. Energy Rev. 13 (4), 887–894.

Sahu, S., Chakraborty, N., Sarkar, P., 2014. Coal–biomass co-combustion: an overview. Renew. Sustain. Energy Rev. 39 (6), 575–586.

Sami, M., Annamalai, K., Wooldridge, M., 2001. Co-firing of coal and biomass fuel blends. Prog. Energy Combust. 27 (2), 171–214.

Service, R.F., 2017. Cleaning up coal-cost-effectively. Science 356.

Sinha, A., Malo, P., Frantsev, A., Deb, K., 2014. Finding optimal strategies in a multi-period multi-leader-follower stackelberg game using an evolutionary algorithm. Comput. Oper. Res. 41 (1), 374–385.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., 2009. Energy. beneficial biofuels-the food, energy, and environment trilemma. Science 325 (5938), 270.

Wang, Q., Li, R., 2017. Decline in China's coal consumption: an evidence of peak coal or a temporary blip? Energy Policy 108, 696–701.

Weldu, Y.W., 2017. Life cycle human health and ecosystem quality implication of biomass-based strategies to climate change mitigation. Renew. Energy 108, 11–18.

Xu, J., Ma, N., Xie, H., 2017. Ecological coal mining based dynamic equilibrium strategy to reduce pollution emissions and energy consumption. J. Clean. Prod. 167, 514–529.

Xu, J., Song, X., Wu, Y., Zeng, Z., 2015. Gis-modelling based coal-fired power plant site identification and selection. Appl. Energy 159, 520–539.

Xu, J., Zhou, X., 2011. Fuzzy-Like Multiple Objective Decision Making. Springer, Berlin, Heidelberg.
Yearwood-Lee, P.B.E., 2015. Carbon emission trading.
Yilmaz, B., Selim, H., 2015. A decision model for cost effective design of biomass based green energy supply chains. Bioresour. Technol. 191, 97–109.
Zhang, G., Lu, J., Gao, Y., 2015. Multi-Level Decision Making. Springer, Berlin, Heidelberg.
Zhang, Q., Zhou, D., Zhou, P., Ding, H., 2013. Cost analysis of straw-based power generation in Jiangsu Province, China. Appl. Energy 102 (2), 785–793.
Zhang, X., Winchester, N., Zhang, X., 2017. The future of coal in China. Energy Policy 110, 644–652.
Zhao, Y., Wang, S., Duan, L., Lei, Y., Cao, P., Hao, J., 2008. Primary air pollutant emissions of coal-fired power plants in China: current status and future prediction. Atmos. Environ. 42 (36), 8442–8452.